MODELLING AND SIMULATION OF BUILDING ENERGY CONSUMPTION: A CASE STUDY ON AN INSTITUTIONAL BUILDING IN CENTRAL QUEENSLAND, AUSTRALIA

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ABSTRACT

Modelling and simulation of energy consumption in Information Technology (IT) building on the Rockhampton campus of Central Queensland University, Australia is presented. Design Builder, commercially available software, was used for the prediction of energy consumption. All the possible sources and uses of energy in building were accounted in the modelling and simulation. The operation of the Heating, Ventilation and Air Conditioning (HVAC) system and the lighting energy consumption of the whole building has been studied in detailed. The factors that affect building energy performance and thermal comforts of the occupants during summer and winter have been identified. Further studies are being carried out to evaluate whole building annual thermal performance and retrofit decision making.

KEYWORDS

Building energy, modelling and simulation, Institutional Building, DesignBuilder, EnergyPlus.

INTRODUCTION

The key reason for building energy modelling and simulation is to understand the building condition and check it against utility bills with a view to reducing the energy consumption of the buildings. Computer based modelling and simulation is a proven technique for evaluating building energy consumption. There are many simulation softwares available these days for whole building performance simulation for example BLAST,DOE 2, eQUEST, TRNSYS, EnergyPlus, Energy Express, EFEN etc.

The Building Loads Analysis and System Thermodynamics (BLAST) tool (Building Systems Laboratory 1999) is employed to predict energy use of a whole building, energy system performance and cost in buildings for long periods. The BLAST program was developed by the U.S. Army Construction Engineering Research Laboratory and the University of Illinois (Krarti 2000). DOE-2.1E (Winkelmann et al. 1993) was developed at the Lawrence Berkeley National Laboratory (LBNL) by US Department of Energy and is used to predict hourly, daily, monthly and/or annually energy use and energy cost of a building considering weather information, building geometric, MVAC description, and utility rate structure. eQUEST is simple building energy analysis tool which produces a detailed simulation of building and estimates how much energy it would use. This software utilizes the full capabilities of DOE-2.2. Within eQUEST, DOE-2.2 performs an hourly simulation of building for a one-year period (Zhu 2005). Energy Plus (Crawley et al. 2001) is a modular, structured software tool based on the most popular features and capabilities of BLAST and DOE-2.1E. Energy Plus provides an integrated (simultaneous loads and systems) simulation for accurate temperature and comfort prediction. DesignBuilder (2006) by DesignBuilder Software Ltd, is a unique tool for evaluating building condition, creates a virtual environment where mechanical ventilation, air conditioning (MVAC) and lighting system of the building are evaluated with relative retrofitted strategies. Current version of DesignBuilder (DB) allows EnergyPlus (EP) as the calculation method to evaluate the energy performance of the building. HVAC system can be modelled using compact HVAC description, which is automatically expanded into full HVAC system data set prior to simulation. Australian Commonwealth Scientific and Research Organization (CSIRO 2004) is in the process of developing simulation software ‘Energy Express’ for Engineers. The first beta version of the software is expected to be released by the end of 2006. ‘Energy Express’ for architects was released early this year. It has got a prototype HVAC system design with more emphasis on façade design and evaluation.

A computer model for the prediction of energy consumption of the Information Technology building of Central Queensland University, Rockhampton, Australia campus has been developed using DesignBuilder and thermal comfort ability of the occupants has been verified. The operation of the Heating, Ventilation and Air Conditioning (HVAC) system and the lighting energy consumption of the whole building for summer and winter have been discussed. The factors that affect building energy performance and thermal comfort of the occupants have been identified.

MODEL DESCRIPTION

Building Description

The building is located in Rockhampton in the Central Queensland region. The building consists of four levels and has a complete air-conditioned floor area. The modelled building has standard construction with lightweight concrete aggregate brick double glazed walls and suspended 10 mm ceiling tiles. Both interior and exterior shading are included in the model. The input data were building constructional records, local climate data, occupancy, internal load, HVAC and lighting component data, equipment data etc. Far too often inputs were assumed according to Building Code of Australia for class 5 building. Description of the building system including operating schedule and power density are shown in Table 1. The modelled building characteristics are as follows:

Building type: Office
Size: 3 storied, nearly rectangular shaped plans with entrance on the ground floor.
Operating Schedule: 8:00 to 18:00 [5 days/week]
Walls: Double Brick Plaster
Roof Ceiling: Concrete and Plasterboard
Floor: Concrete slab with carpet
Internal Partition: Lightweight 2X25 mm gypsum plasterboard with 100 mm cavity
Component Block: Lightweight concrete block
Thermal Mass Construction: 130 mm concrete slab
Front Orientation: NE
Width: 34 m
Length: 74 m
Total Height: 16 m
No of Floors: 4
Windows Width 1.5 m
Windows Height 1.5 m
Type: Single glazed, clear float ¼ inch with blinds
Occupancy: 1 person per $10m^2$
Outside air rate: 10L/s/person
Window Shading: Blind with high reflective slats
Local Shading Type: Overhang and side fins
Lighting Type: Compact fluorescent
Lighting Power Density: $18w/m^2$
Office Equipment Power Density $15w/m^2$
Cooling Type: Air Cooled
Cooling Power Density $40w/m^2$
Ventilation Power Density $5w/m^2$

HVAC Plant Description

The four levels of the building are air conditioned from a number of separate and independent air handling systems. Each air handling unit consists a chilled water-cooling coil, disposable media air filter bank and centrifugal supply air fan. Conditioned supply air and return air is ducted to the respective areas in insulated sheet metal ducting. Ceiling diffusers are provided with sidewall registers. Fresh air is ducted to each air-handling unit from a wall Louvre. Dampers are provided to each unit and these have been set at the time of commissioning to the required air quality. All air-handling units operate under time switch control, the time switch being located within the respective switchboard. Each unit is provided with a manually operated by-pass control station to enable after hours operations. Activation of the local bypass push button energises the supply fan and hence the control the system for a period. At the expiry of this period, the unit will revert to normal time switch control.

Cooling is provided by a central chilled water system through two equally sized, reciprocating, air-cooled chiller sets. The chiller sets and associated circulating pumps are located on the roof deck plant enclosure. Chilled water at approximately 6.5^oC is circulated through the cooling coils of the fan coil units. A motorised control valve in response to a 0-10 volt signal from the electronic temperature control system regulates the flow of water through each coil. Unrequited chilled water is automatically bypassed back to the chillers so that an approximately constant chiller vessel flow is maintained. Except for two air-handling units which are provided with three way control valves, all other units have two way valves fitted. Each chiller, once operative, stages compressor steps in response to its internal leaving water temperature control system. The two chillers operate in a lead/leg arrangement, subject to building load. To maintain the system at a positive pressure and to compensate for small system losses, a 250-litre head tank is provided and located at high level at the chiller deck. A cooling call from any air handling unit, through an adjustable time delay initially set at 10 minutes, starts the lead chilled water pump and energise the controls of the associated chiller. The chillers set then load and unload stages of capacity in response to its inbuilt control system based on sensing leaving water temperature to control at a set point of 3.5^oC. The condenser fans are cycled in line with the capacity modulation, again from the inbuilt chiller control module. A system manger is provided for total management of the sequencing of the two chillers. The feature of the system manager enables the lead/leg staging to be alternated and re-sequencing the lead portion should it be found to be faulty.

Weather of Rockhampton

Rockhampton climate is classified as Subtropical (Chowdhury et al. 2006). The city is situated on the Tropic of Capricorn and lies within the southeast trade wind belt, too far south to experience regular northwest monsoonal influence, and too far north to gain much benefit from higher latitude cold fronts. Rockhampton's average annual rainfall is a little over 800 mm. Rainfall average suggests a distinct wet and dry season, with the wet season generally December to March and the dry season June to September. Generally, summer is from December to February and winter is from June to August. For the simulation, extreme hot summer period was selected from January 27 to February 2 and nearest maximum summer temperature was taken 39°C. In typical summer week, the nearest average temperature is 26.38°C. Extreme cold winter week is selected from June 8 to June 14 and nearest minimum temperature for winter is 5.00°C. In typical winter week the nearest average temperature is 16.99°C. Figure 1 and 2 show typical Rockhampton data for summer and winter.

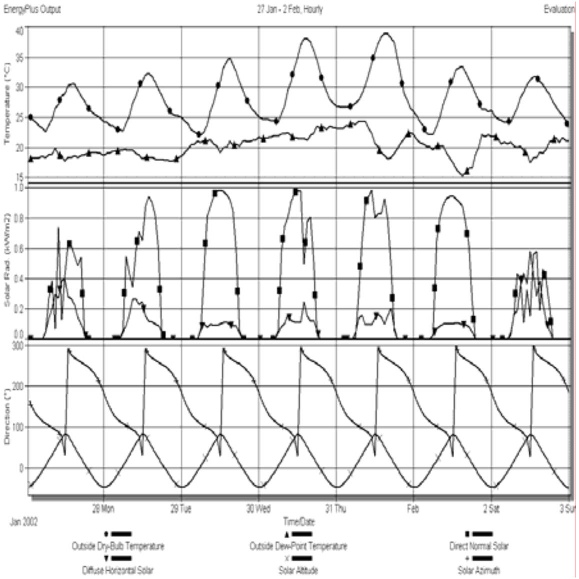

Figure 1: Summer week site data

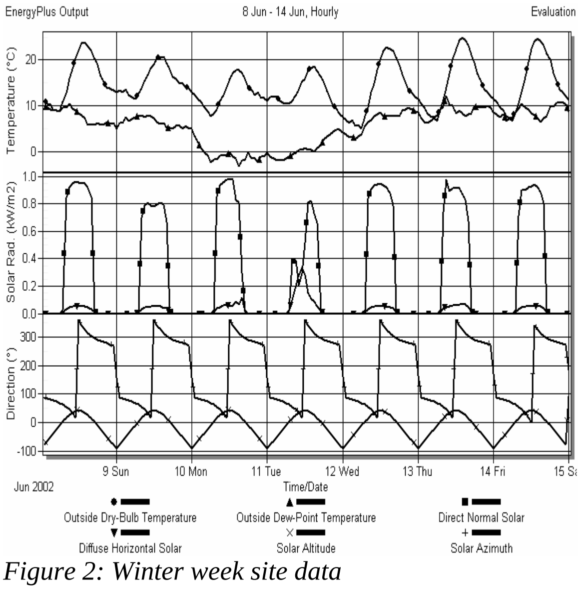

Figure 2: Winter week site data

MODEL LAYOUT

DB models were structured in order of Site, Building, Block, Zone, Surface data. This structure sets up data globally in a building model. Building blocks are basic geometric shapes that are used to assemble a 3D model as similar to building physical model using bricks. Component blocks are added to the building to create non air-conditioned spaces, visual and shading structures which do not contain zones and are not part of the model. In the modelled building (Figure 3), building blocks, which represent the outer shell of the model or part of the model, are composed of building elements such as walls, floor slabs and roofs, and are partitioned internally to form thermal zones. CAD data in the form of 2D layouts of the particular building is imported into DB in order to trace blocks and block partitions. The geometric model of the building was first created based on the world coordinate systems and then the model was rotated 345 degree according to azimuth angle of the actual building. The partition of the space boundaries of the thermal zones were modelled according to the HVAC drawing for the consistency in specifying according to building management system. DB uses the thermal characteristics of the constructions for each of the walls, floors, roofs, partitions etc. in each zone and accounts for the thermal mass in the simulations. The defined thermal mass was lumped together for each zone and modelled in EP. The features discussed in the building description section were major consideration for creating the geometric model.

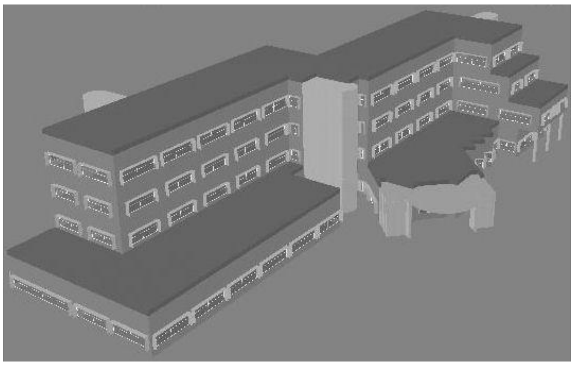

Figure 3: Geometric representation of the building

HEATING AND COOLING DESIGN CALCULATION

Heating and cooling design calculations use simple worst-case winter and summer design data from ASHRAE respectively. The calculations were carried out to determine the size of the heating and cooling equipment required to meet the coldest and hottest winter and summer condition likely to be at Rockhampton. Heating and cooling design calculations were done by putting a sin curve through maximum daytime and corresponding night-time summertime design temperatures. The daily temperature profile used in the cooling design calculations was calculated from the maximum and minimum values and assuming that the maximum temperature lags maximum solar elevation by 3 hours. By default EnergyPlus assumes that air temperature within a zone is completely uniform (i.e. the air is fully mixed). The weather data used in winter design calculations were minimum outside dry bulb temperature (design outside air temperature), co-incident wind speed and direction. The weather data used in summer design calculation were maximum outside dry bulb temperature (maximum dry bulb air temperature over the day), minimum outside dry bulb temperature (minimum dry bulb air temperature, night time), and wet bulb temperature at the time of the maximum dry bulb temperature.

Heating design calculation predicted the heat loss of each zone of the building at steady state with no solar gain. This was based on worst-case winter design data for the location of the building. The calculation is shown in the graph (Figures 4 and 5) highlighting air temperature, radiant temperature, comfort temperature, outdoor temperature, and heat gain and losses.

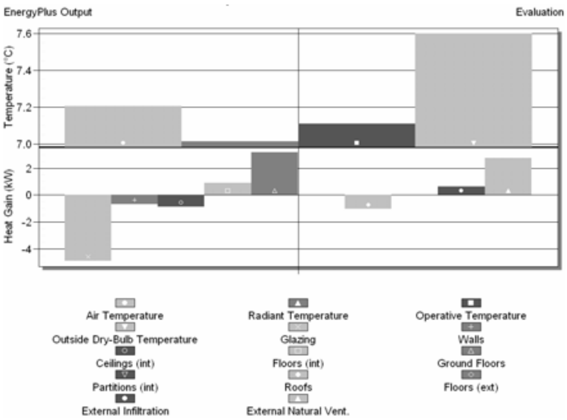

Figure 4: Temperature and Heat loss of the building

The cooling design calculations were based on simplified sinusoidal worst-case summer design conditions. The cooling design profile is shown in Figure 5. The results comprise temperature, heat losses and gain in relation to cooling design. The average air temperature of the air-conditioned spaces of the building is within the range of twenty which also meets the comfort temperate range as per Australian standard.

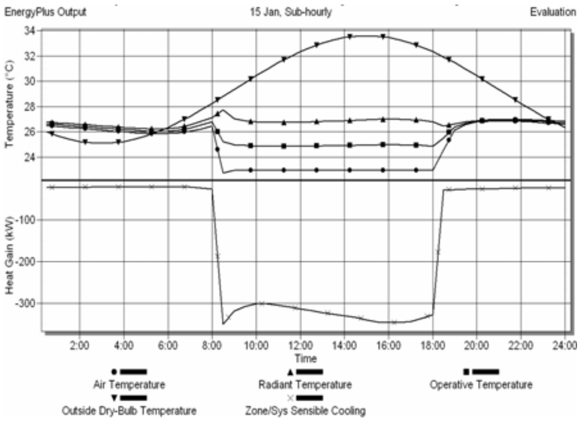

Figure 5: Cooling design temperature profile

INTERNAL GAINS

The types of internal gain include occupancy, computer, office equipment, and lighting gains etc. The operating time was defined on the basis of a typical workday basis by a start time, end time, working days per week and seasonal variation. In some cases, the load data associated with each zone were taken as the average for a specific zone or for the whole building. When defining internal loads, geometric information, infiltration method and day lighting are also specified. The heating/cooling systems were defined in DB using Compact HVAC descriptions but modelled in EP. DB is used to automatically calculate heating and cooling capacity in each zone based on the output from the heating and cooling design calculations. The occupancy model data defines the number of people in the space and the times of occupancy. But for the case study building the Occupancy schedule setting (Typical workday or Schedule) was used to control internal gains and/or HVAC systems by defining appropriate Model options. When the Schedule Timing model option is set, the occupancy times are controlled by a Schedule. The metabolic gains for the zone were multiplied by the value of the schedule at each time step in the simulation. The internal heat gain were calculated using the following formula

*Equipment or Lighting gain = Thermal Gain/m² *area * value in EP compact schedule at a date and hour.*

The internal heat gain due to lighting, occupancy, transmitted solar heat, computer and other office equipment are shown on an hourly basis in Figure 6 and 7 for a typical summer and winter day. The highest heat gain is due to solar transmittance both in summer and winter. The next priority gains are due to occupancy and lighting, computer and office equipment. The cooling requirement throughout the day remains approximately same with an exception during the start of the day. Figures 6 and 7 also show the cooling requirement which is almost one third in winter compared to summer. Internal heat gain after hours and in the early morning is almost negligible.

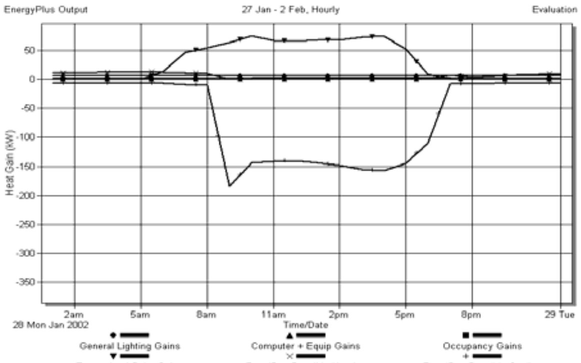

Figure 6: Internal heat gain and cooling energy delivered in a typical summer day

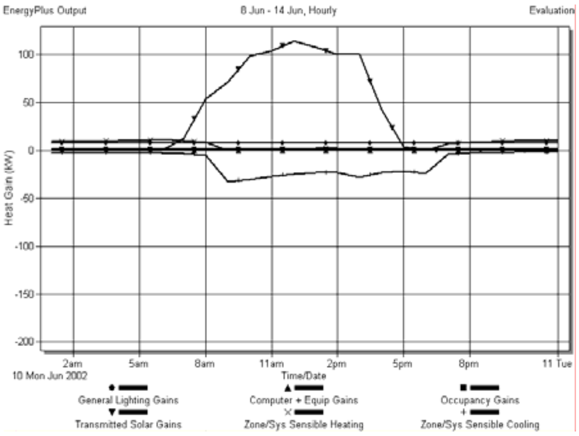

Figure 7: Internal heat gain and cooling energy delivered in a typical winter day

The fabric and ventilation heat gain in summer and winter are shown in Figures 8 and 9 respectively. These figures show the heat losses due to glazing, walls, roofs, ceiling, and external infiltration related to the number of air changes to the building and heat gain due to internal floor and external mechanical ventilation for both summer and winter season. The highest heat losses and gains are due to glazing and external ventilation.

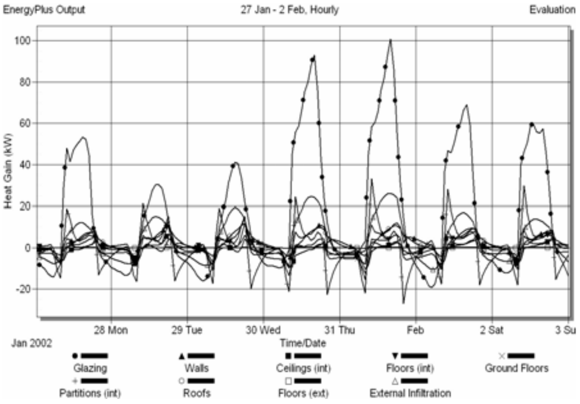

Figure 8: Fabric and ventilation heat gain in summer

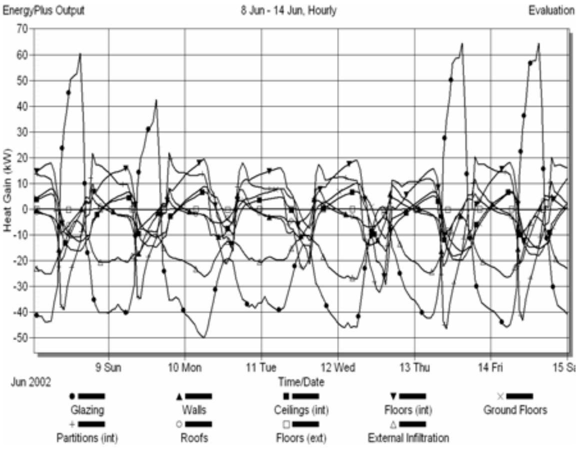

Figure 9: Fabric and ventilation heat gain in winter

COMFORT

The DB simulates extensive data on environmental conditions within the building and occupants' comfort level. Figures 10 and 11 provide internal temperature, humidity, discomfort hours and thermal comfort index for a typical summer and winter day.

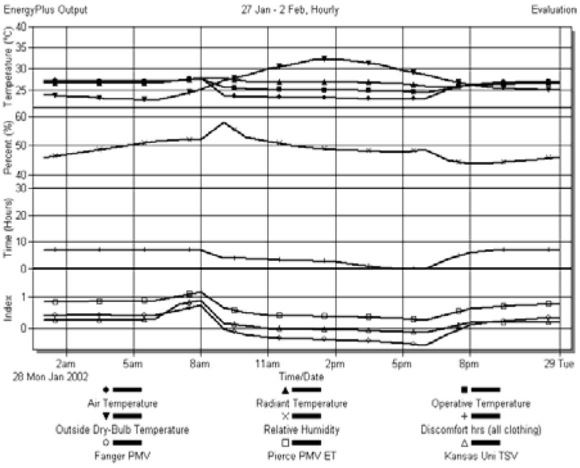

Figure 10: Hourly comfort profile in a typical summer day

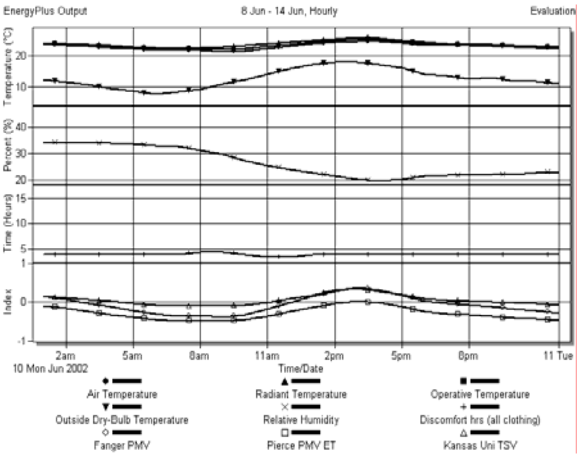

Figure 11: Hourly comfort profile in a typical winter day

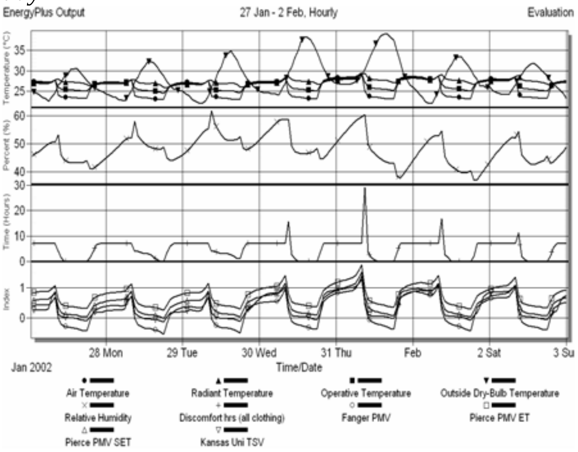

Figure 12: Hourly comfort profile in a typical summer week

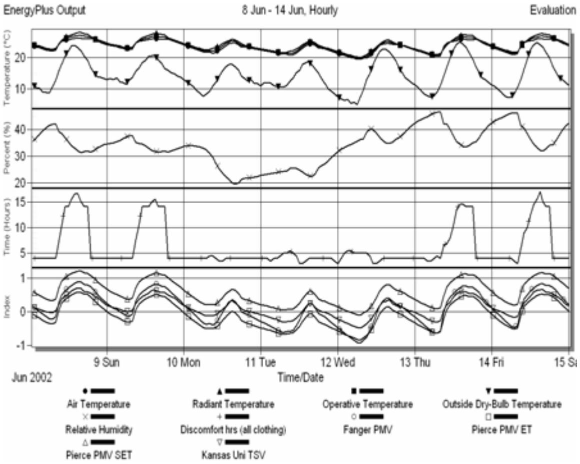

Figure 13 Figure 11: Hourly comfort profile in a typical winter week

Figures 12 and 13 provide the same for a typical summer and winter week. The temperature and humidity level are consistent and maintained considerably within the comfort level. The discomfort hours are zero in winter and almost negligible in summer. Through the simulation, the current indoor environmental control strategies have been checked and thermal comfort ability of the building has been determined. Thermal comfort index (Fanger PMV, Pierce PMV and Kansas TSV) has also been simulated on nine point thermal sensational scale and results are with in ±1 where +1 stands for slightly warm and -1 stands for slightly cool.

ENERGY END USE

Compact HVAC data template was used to organise simulation data at the building and zone level. The system availability schedule was used at the building level for unitary multizone systems. Simulation was carried out on detailed HVAC component models automatically generated from the compact description. The unitary multizone option was selected to model constant volume direct-expansion based HVAC configurations. In this system, central heating and cooling coils are used to condition air which is delivered to the each of the zones in the system through an air delivery system. Air delivery is set up to ensure minimum fresh air supply (DesignBuilder User Manual 2006). The thermostat is located in the control zone as set out by the thermostatic control zone for unitary system at zone level. The thermostat position is setup in a zone in such a way that it indicates representative temperature for the whole building; otherwise some zones will become over/under heated/cooled. Only one unitary multizone system is defined at building level and in all zones which are part of the system. Other zones have unitary single zone which take all their data from the zone level. The Cooling capacity is auto sized using the Cooling Design Calculations. The chiller coefficient of performance is used to calculate the fuel consumption required to meet cooling demand. It represents the total seasonal efficiency of the chiller excluding losses or consumption due to external pumps and fans but including all energy consumed by such ancillary devices within the chiller. Chiller COP data is specified for the whole building. The cooling distribution loss is the loss of heat (cooling energy) due to the distribution of cold water/air around the building. It is used to increase the cooling load prior to calculating chiller energy consumption. The formulae for electricity and chiller energy consumption are

Chiller energy = Chiller COP x (EnergyPlus cooling loads + Cooling distribution loss)
*Fuel Use = (Load * Distribution Loss Factor) / Seasonal COP*

The whole building energy simulation has been performed based on data from the nearest available hourly weather station (Rockhampton). Performance of the building for summer and winter has been simulated to check whether the building is performing as expected or not. The simulation of the building helps to study the building operation strategies due to seasonal variation. It is noticed that there is no significant occupancy and internal gain in the building during weekends and holidays.

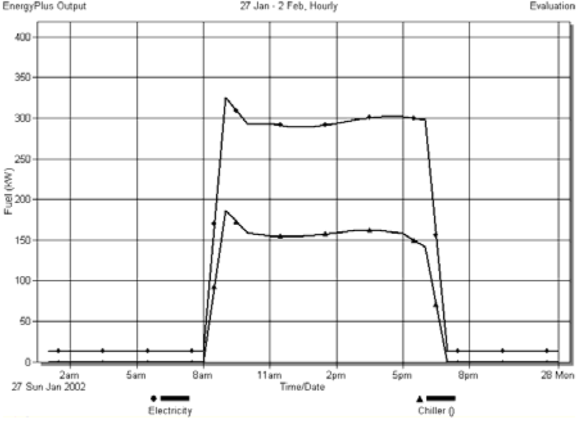

Figure 14 Hourly electricity consumption in a typical summer day

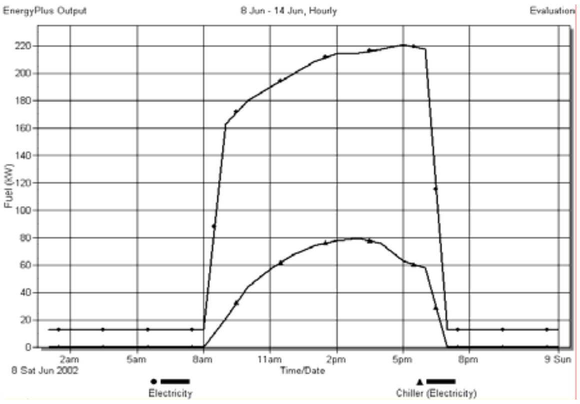

Figure 15 Hourly electricity consumption in a typical winter day

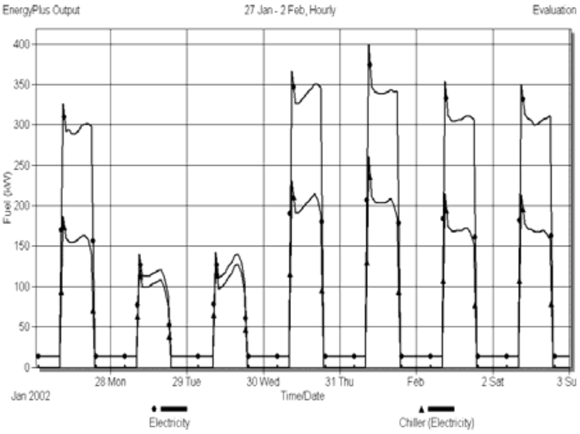

Figure 16 Daily electricity consumption in summer week

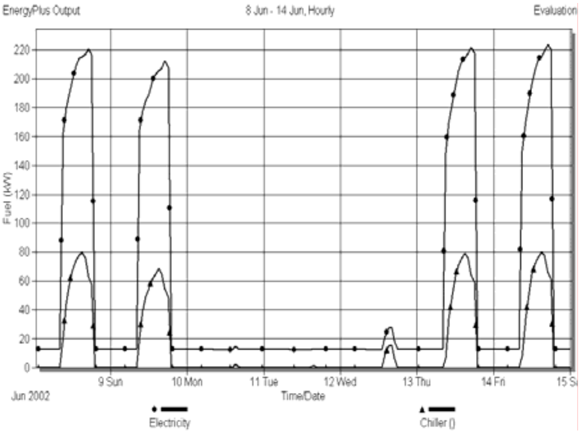

Figure 17 Daily electricity consumption in winter week

The hourly energy requirement of the building and the chiller in a typical summer and winter day and the hourly variation are shown in Figures 15 and 16. It is higher in the summer months and gradually lower in the cooler months. The highest cooling energy is required in summer at the start of the day, which is nearly 325 kW and 220 kW in winter at the end of the day. Figures 16 and 17 show the total electricity and chiller energy consumption by the building in summer and winter. It is typically similar to the building cooling requirement due to internal heat gain and outdoor air temperature. It can be noted from the energy simulation that the electrical energy use increases during the summer months (December to February) when the outdoor air temperatures are high. During winter, the consumption is relatively lower and the variation of electrical energy consumption is consistent and can be attributed mostly to internal heat gain by lighting, office equipment and occupancy. Best fit lines of the normalised energy consumption (kWh/m^2) illustrated in Figures 18 and 19 is the average of all the consumptions in summer and winter months. By the best fit line, it is possible to predict the normalised consumption on a daily basis. The simulated results depicts that the daily electricity consumption of the building varies from 0.5 kWh/m^2 to 0.59 kWh/m^2 in summer and from 0.37 kWh/m^2 to 0.43 kWh/m^2 in winter.

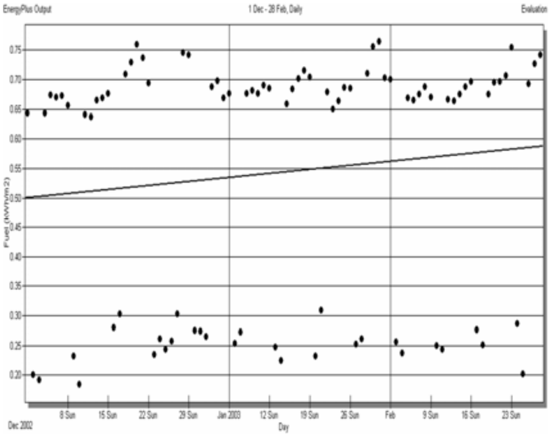

Figure 18 Normalised daily electricity consumption in summer (Best fit line)

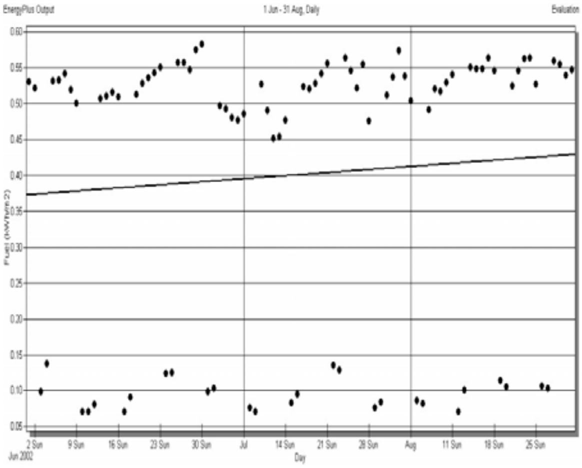

Figure 19 Normalised daily electricity consumption in winter (Best fit line)

CONCLUSION

Simulation of energy performance for an institutional building in Central Queensland, Australia has been carried out. Necessary data and information of the building have been collected and measured on site as the input of the model. The factors that affect building energy performance and thermal comforts of the occupants during summer and winter have been identified. Simulation of the whole building for summer and winter season show that the thermal comfort level is maintain fully and in most cases it is within comfort zone. Sources of the heat gain and typical effect on the whole building has been predicted. The energy consumption profile of the whole building illustrates the total energy consumption and range of maximum demand by the building system. It is shown that DB is one of the best interfaces to model building energy performance through EP based simulation. Further studies are being carried out to evaluate whole building annual performance and retrofit decision making.

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Table 1Description of building systems

Equipment	Type	Power Density (w/m^2)	Schedule
Lighting	Fluorescent	15	08:00-midnight
Office Equipment	Standard	15	08:00-18:00
Cooling	Air-Cooled	40	08:00-18:00 (in few area areas 24 hrs)
Ventilation	Standard	5	08:00-18:00